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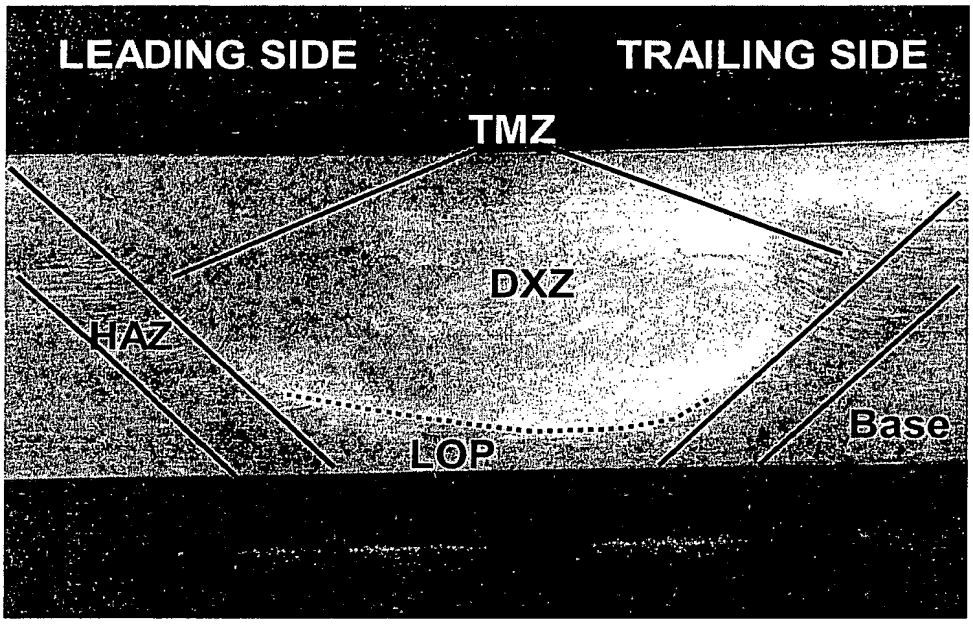

FIG 1

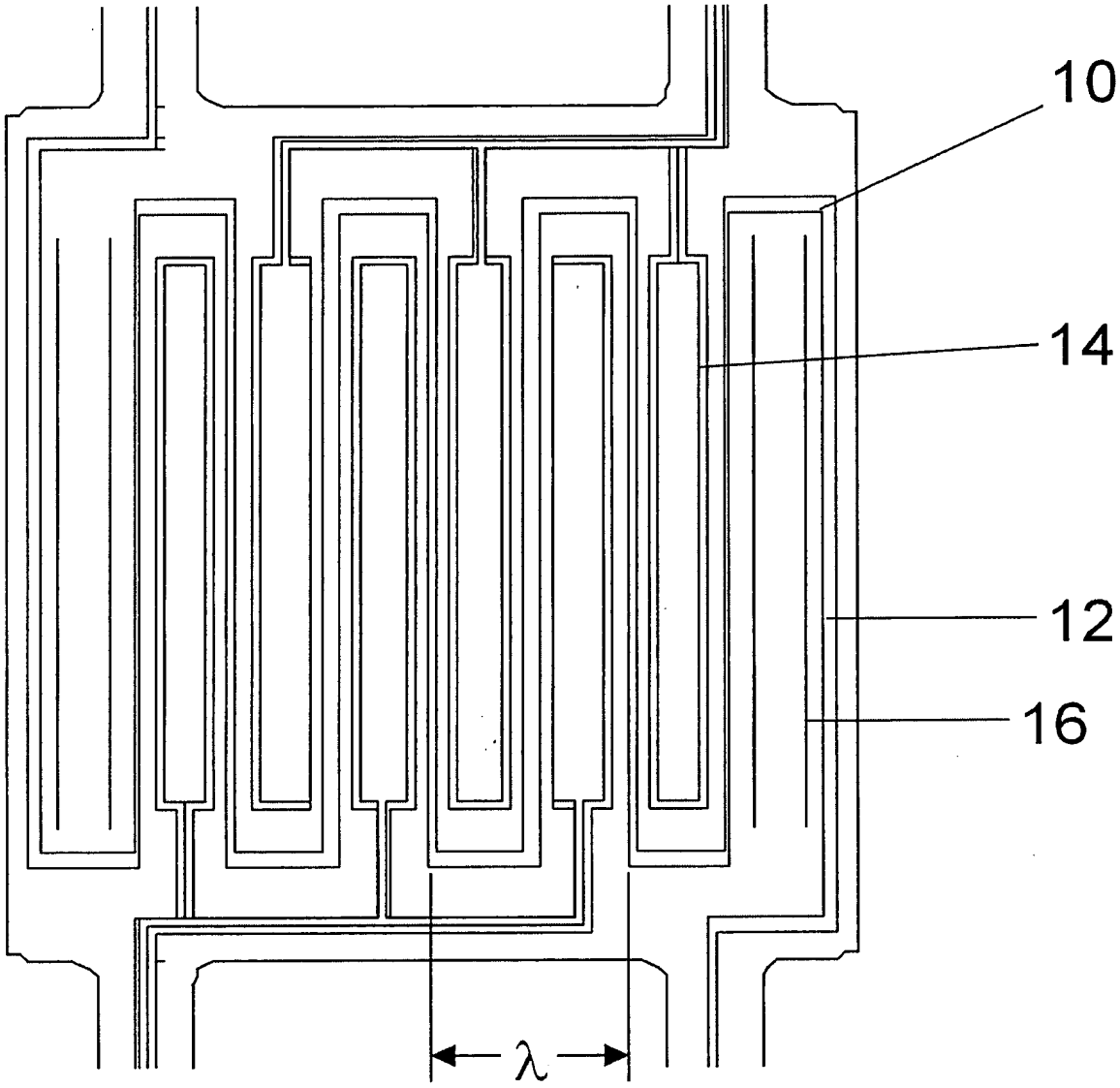

FIG 2

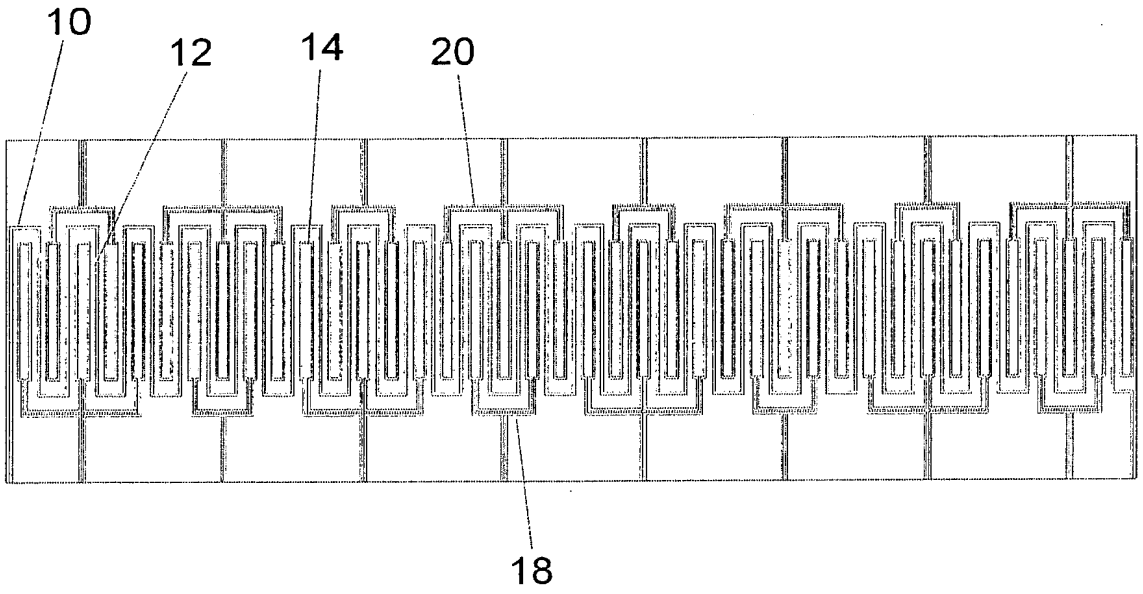

FIG 3

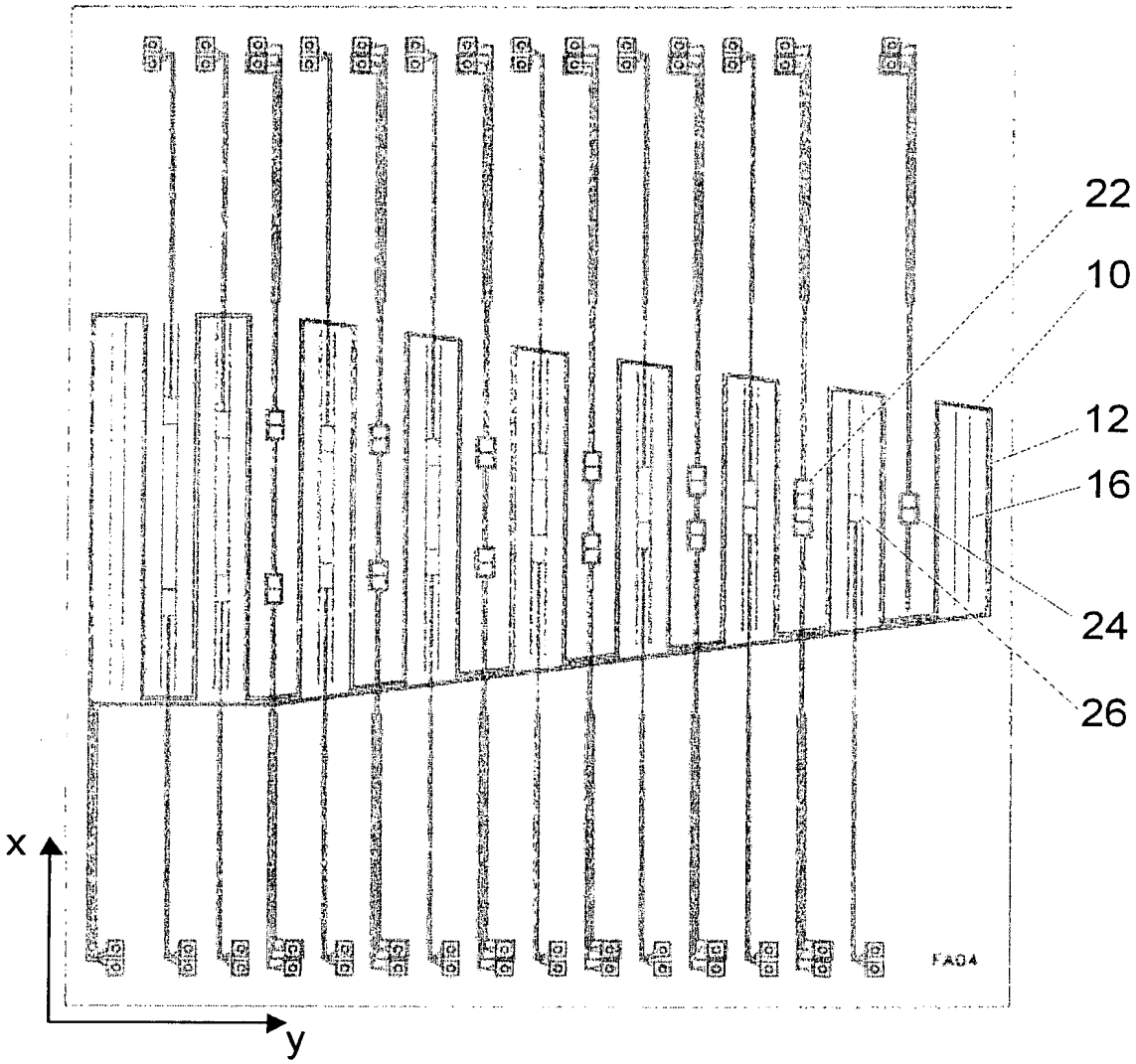

FIG 4

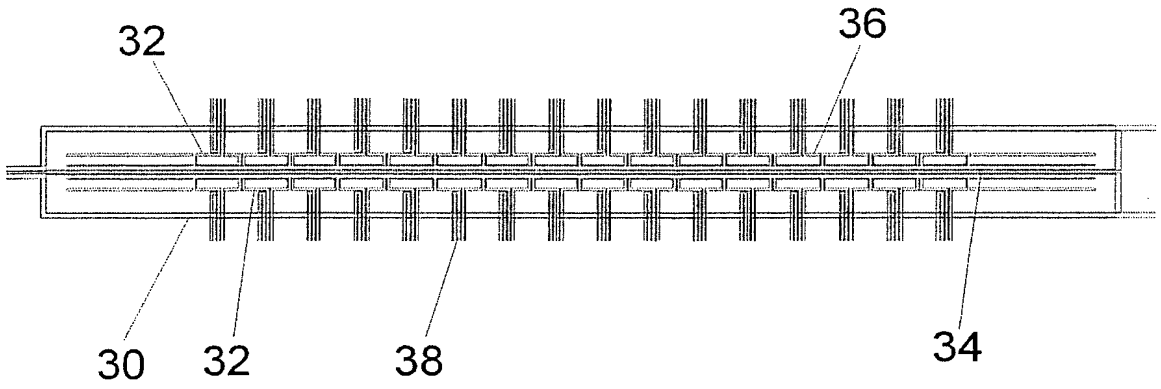
32
36
30
32
38
34

FIG 5A

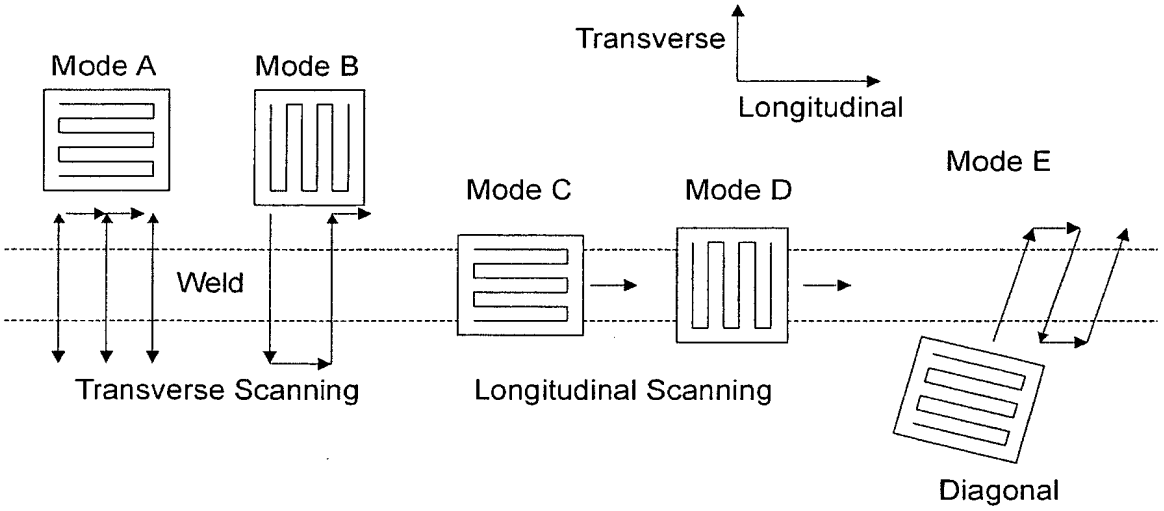
Mode A
Mode B
Transverse
Longitudinal
Mode C
Mode D
Mode E
Weld
Transverse Scanning
Longitudinal Scanning
Diagonal

FIG 6

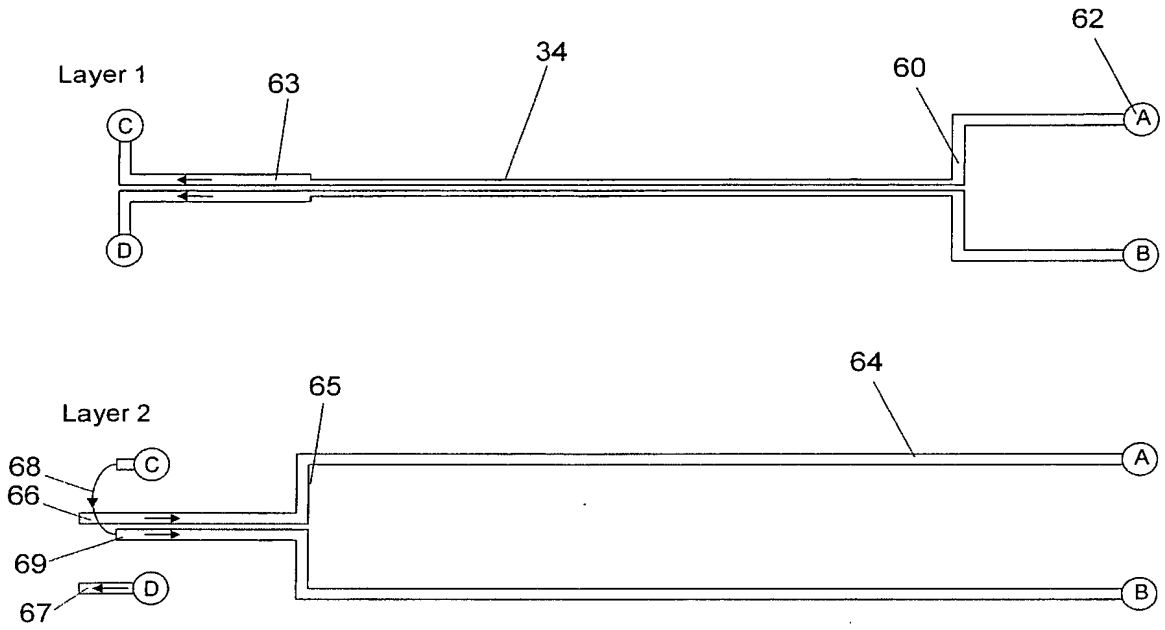

FIG 5B

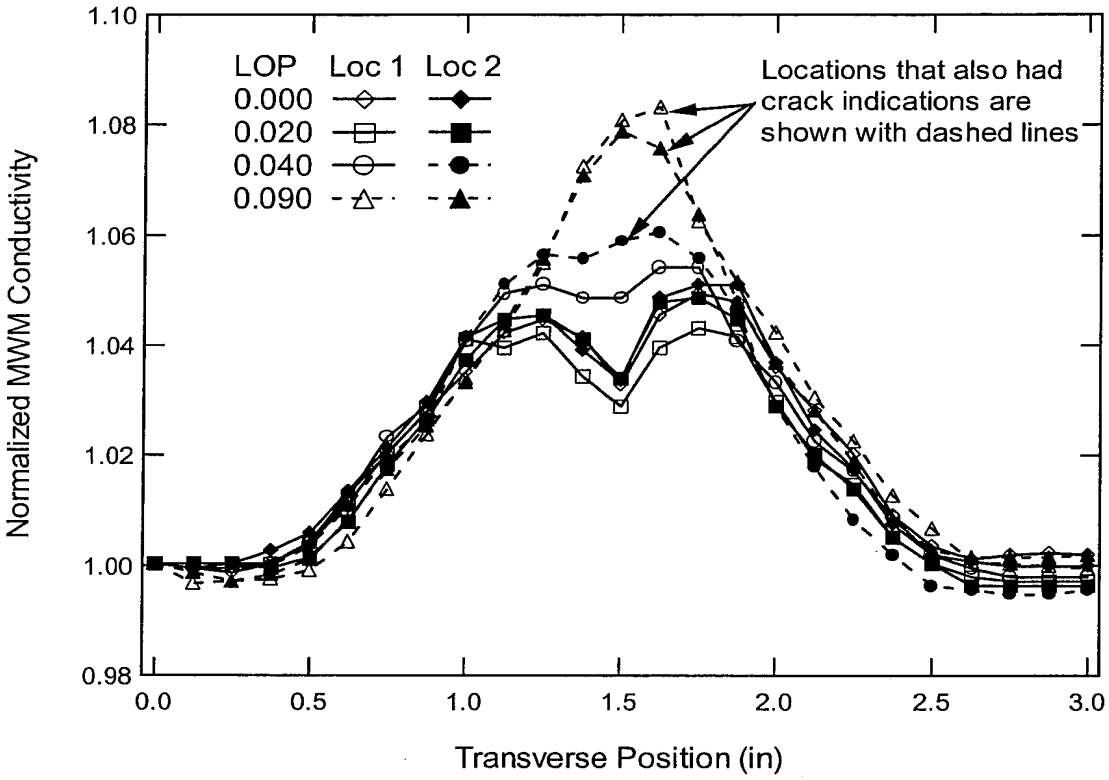
LOP Loc 1 Loc 2
0.000
0.020
0.040
0.090
Locations that also had crack indications are shown with dashed lines
Normalized MWM Conductivity
1.10
1.08
1.06
1.04
1.02
1.00
0.98
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Transverse Position (in)

FIG 7

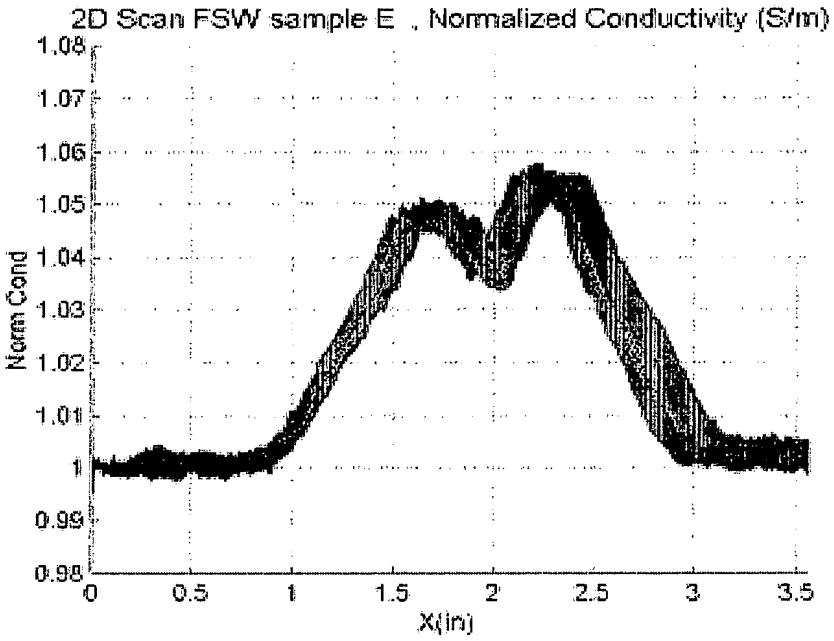
2D Scan FSW sample E , Normalized Conductivity (S/m)
Norm Cond
1.08
1.07
1.06
1.05
1.04
1.03
1.02
1.01
1
0.99
0.98
0
0.5
1
1.5
2
2.5
3
3.5
X(in)

FIG 8

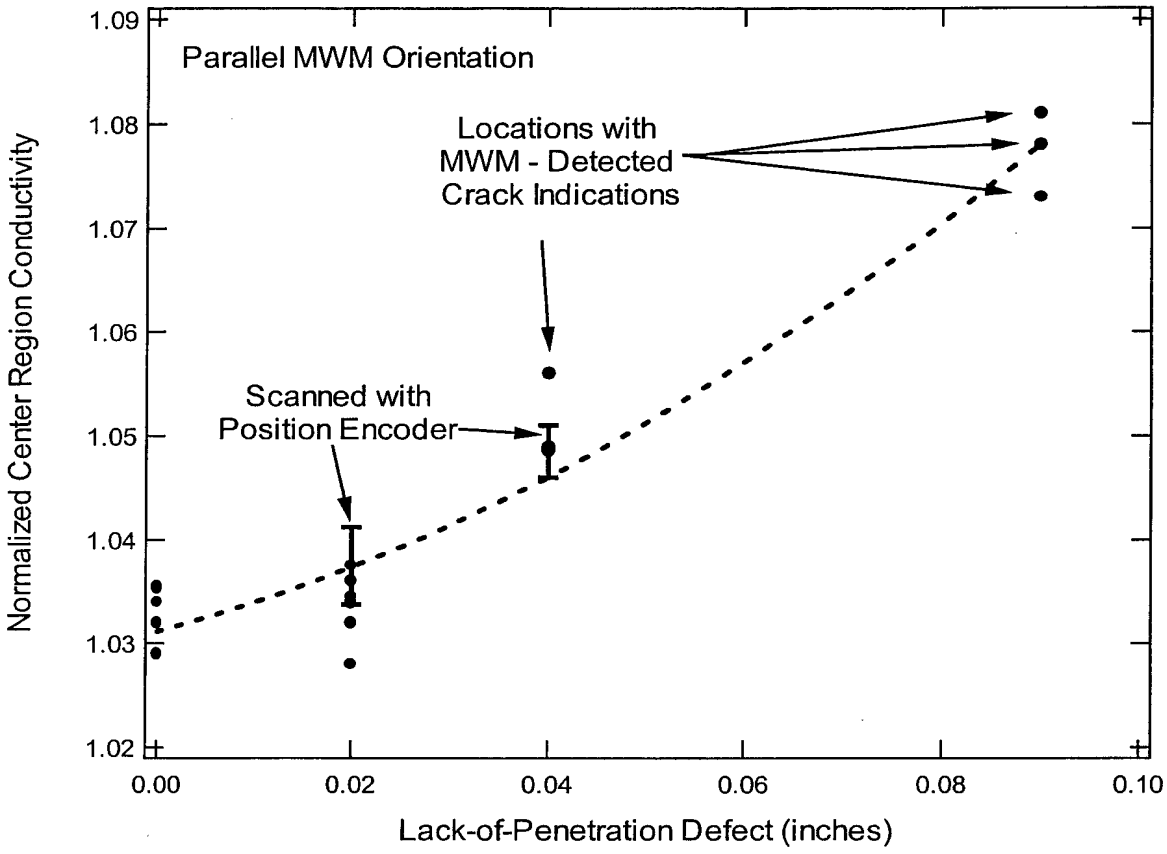
Parallel MWM Orientation
Locations with
MWM - Detected
Crack Indications
Scanned with
Position Encoder
Normalized Center Region Conductivity
1.09
1.08
1.07
1.06
1.05
1.04
1.03
1.02
0.00
0.02
0.04
0.06
0.08
0.10
Lack-of-Penetration Defect (inches)

FIG 9

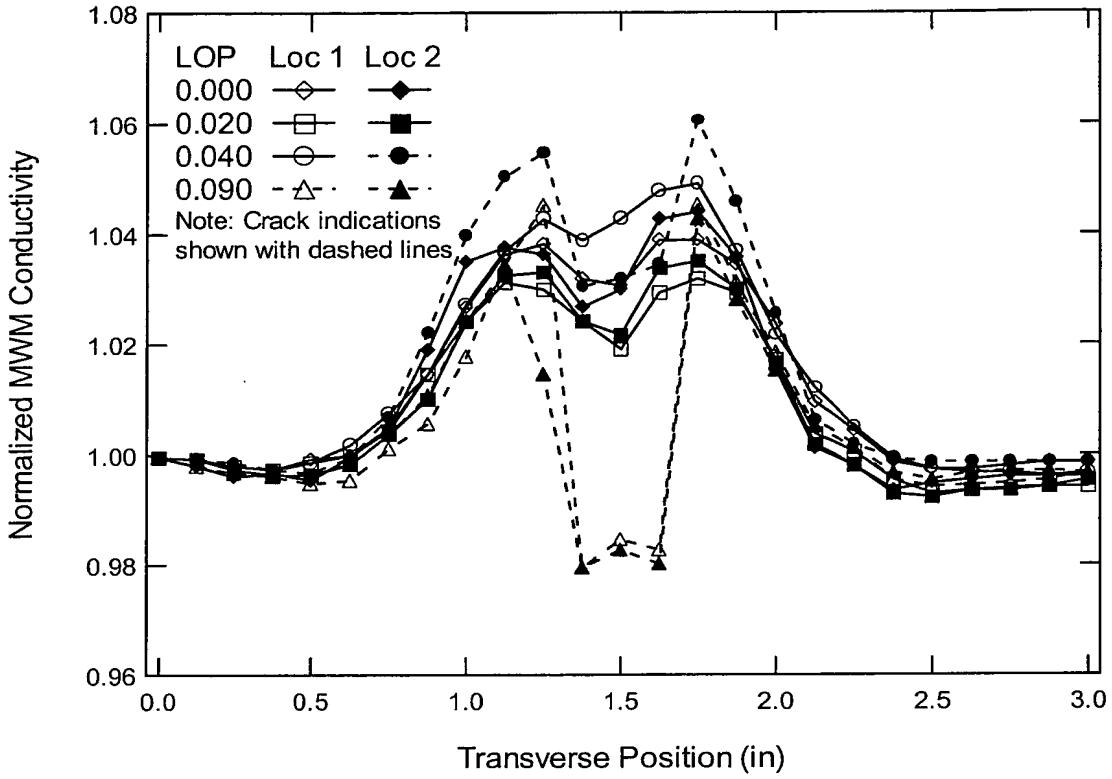
LOP Loc 1 Loc 2
0.000
0.020
0.040
0.090
Note: Crack indications shown with dashed lines
Normalized MWM Conductivity
1.08
1.06
1.04
1.02
1.00
0.98
0.96
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Transverse Position (in)

FIG 10

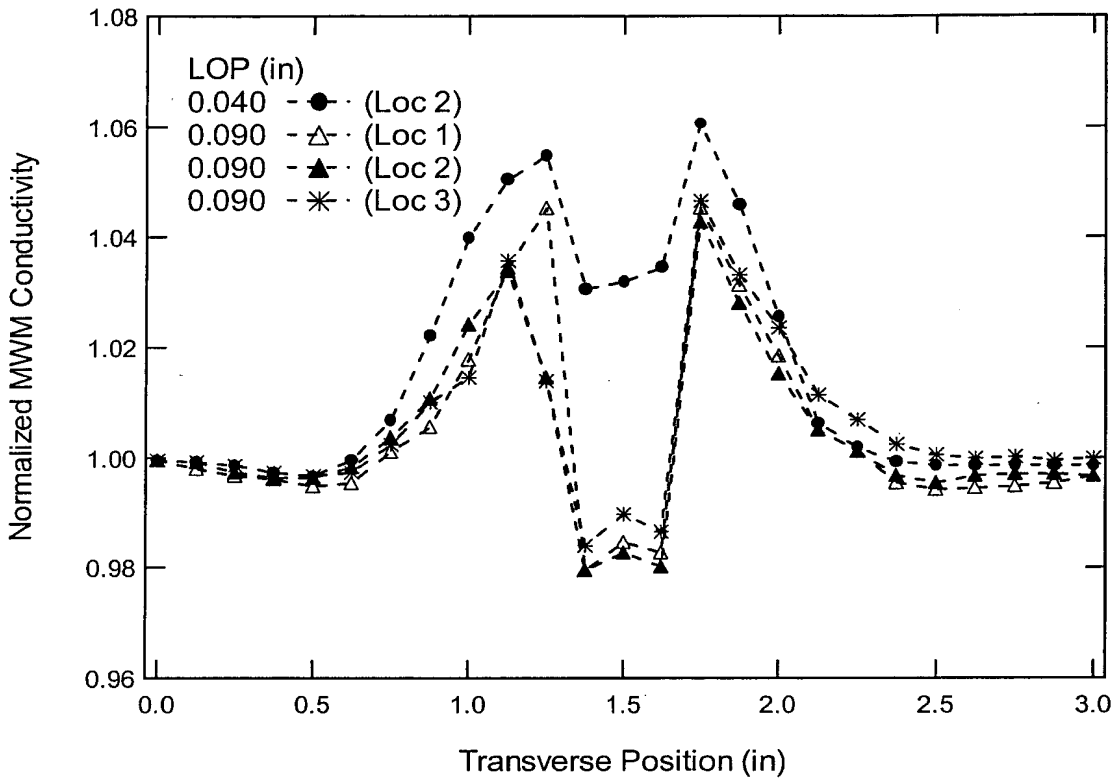
LOP (in)
0.040 (Loc 2)
0.090 (Loc 1)
0.090 (Loc 2)
0.090 (Loc 3)
Normalized MWM Conductivity
Transverse Position (in)
1.08
1.06
1.04
1.02
1.00
0.98
0.96
0.0
0.5
1.0
1.5
2.0
2.5
3.0

FIG 11

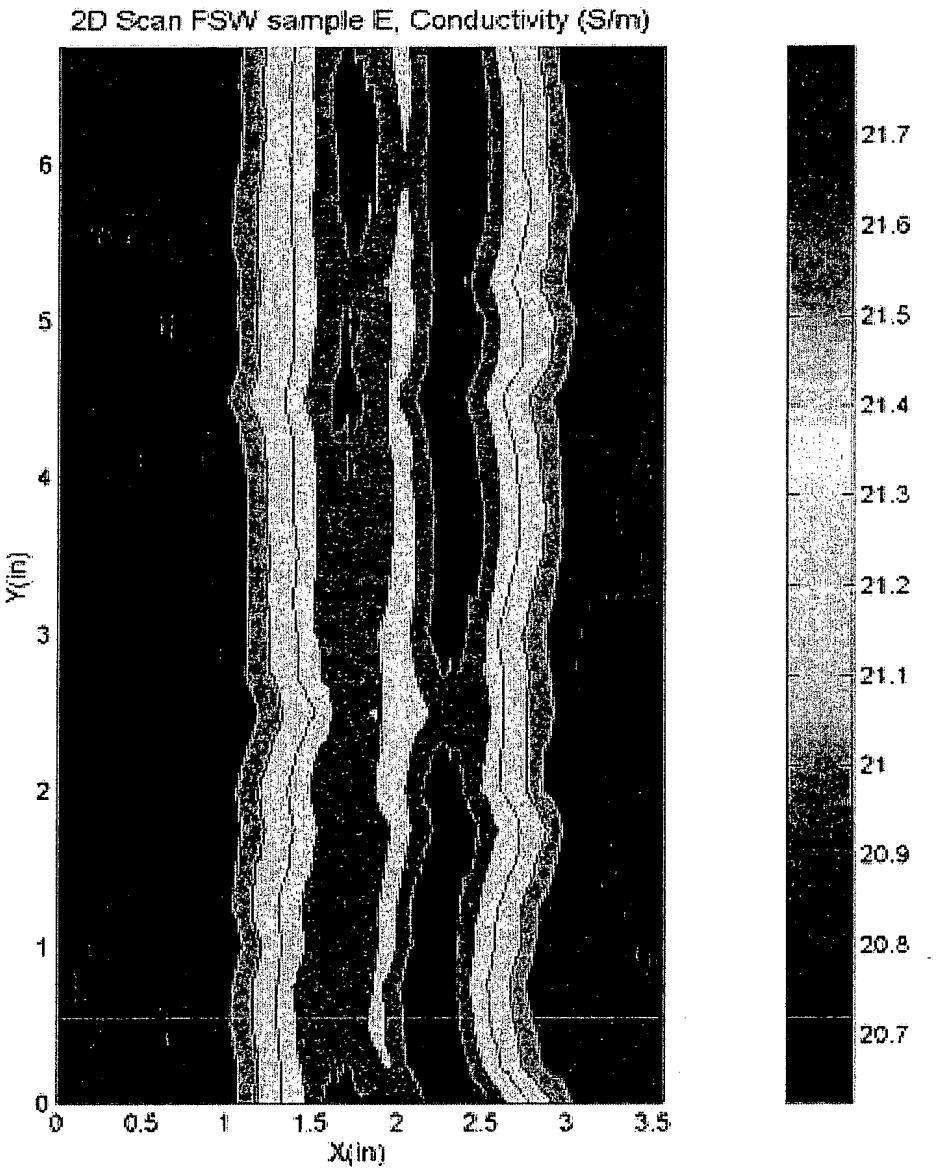
2D Scan FSW sample E, Conductivity (S/m)
Y(in)
X(in)
0
1
2
3
4
5
6
0
0.5
1
1.5
2
2.5
3
3.5
21.7
21.6
21.5
21.4
21.3
21.2
21.1
21
20.9
20.8
20.7

FIG 12

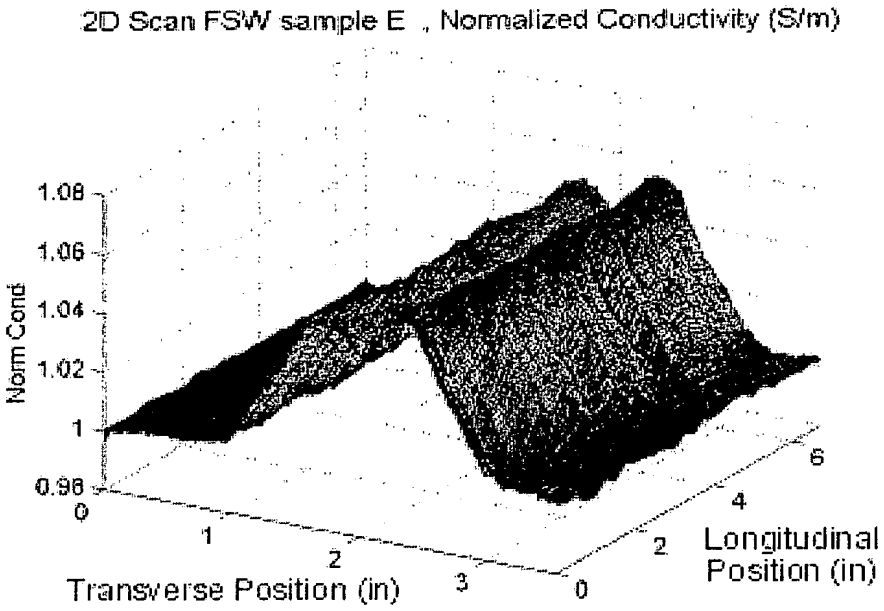
2D Scan FSW sample E , Normalized Conductivity (S/m)
Norm Cond
1.08
1.06
1.04
1.02
1
0.98
0
1
2
3
Transverse Position (in)
0
2
4
6
Longitudinal Position (in)

FIG 13

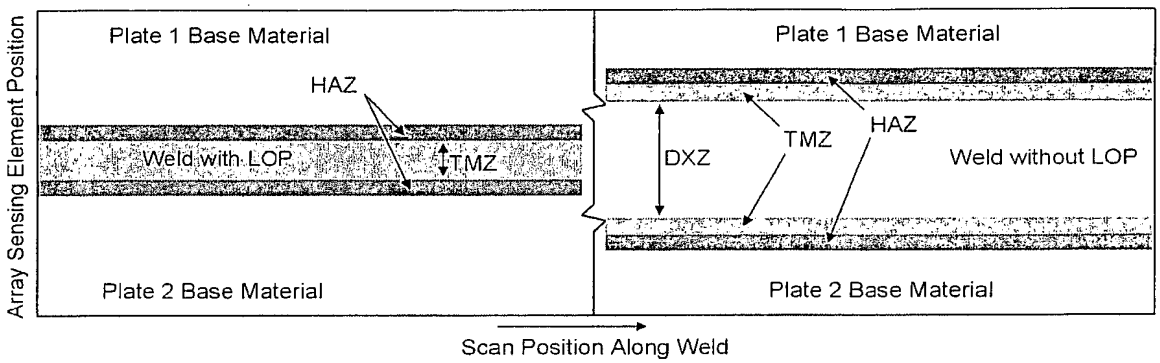
Plate 1 Base Material
Plate 1 Base Material
HAZ
Weld with LOP
TMZ
DXZ
TMZ
HAZ
Weld without LOP
Plate 2 Base Material
Plate 2 Base Material
Array Sensing Element Position
Scan Position Along Weld

FIG 14

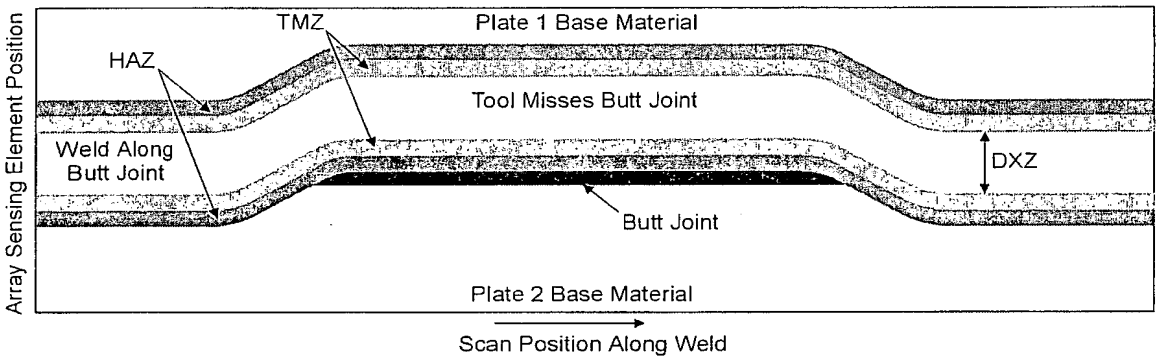
TMZ
Plate 1 Base Material
HAZ
Tool Misses Butt Joint
Weld Along
Butt Joint
DXZ
Butt Joint
Plate 2 Base Material
Array Sensing Element Position
Scan Position Along Weld

FIG 15

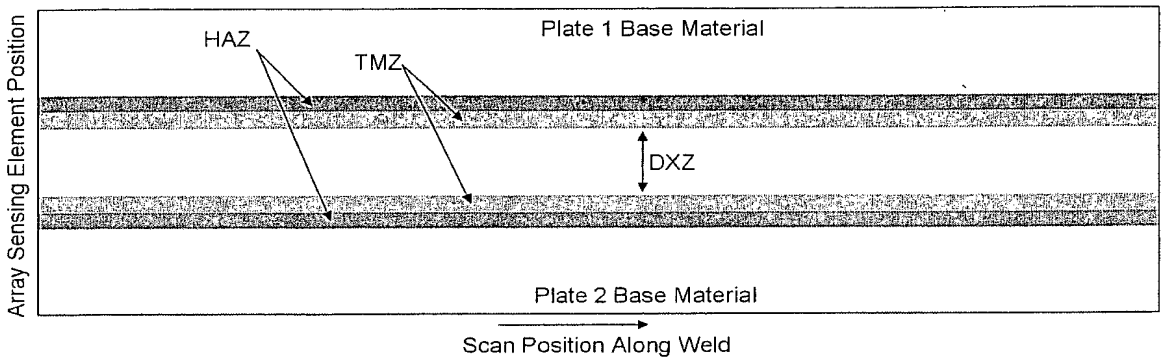
Plate 1 Base Material
HAZ
TMZ
DXZ
Plate 2 Base Material
Array Sensing Element Position
Scan Position Along Weld

FIG 16

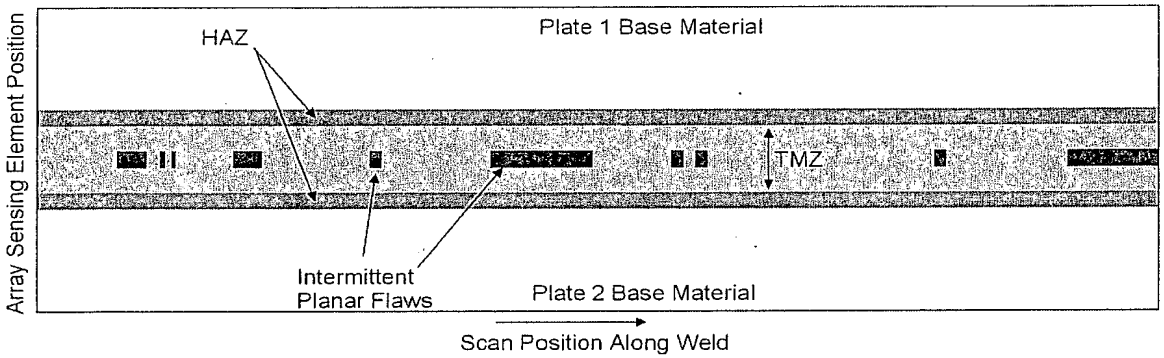
Plate 1 Base Material
HAZ
TMZ
Intermittent
Planar Flaws
Plate 2 Base Material
Array Sensing Element Position
Scan Position Along Weld

FIG 17

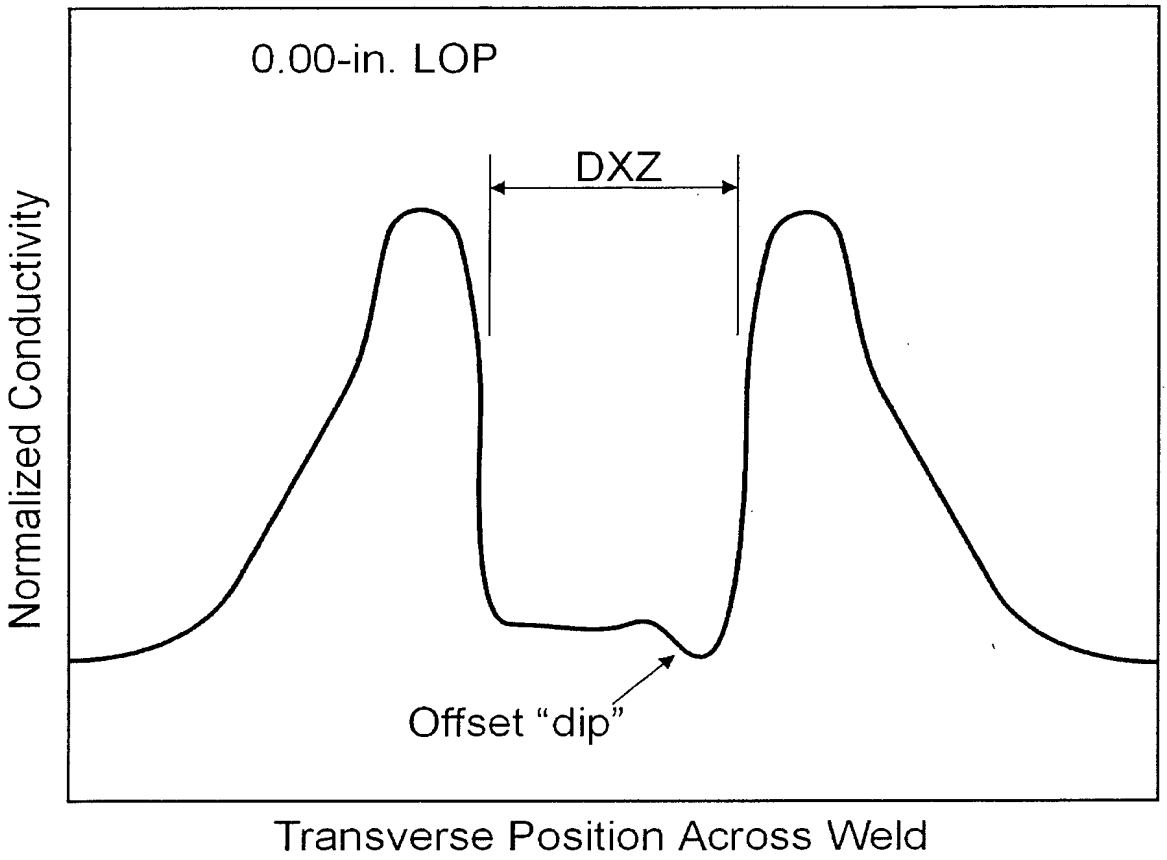
0.00-in. LOP
DXZ
Normalized Conductivity
Offset "dip"
Transverse Position Across Weld

FIG 18

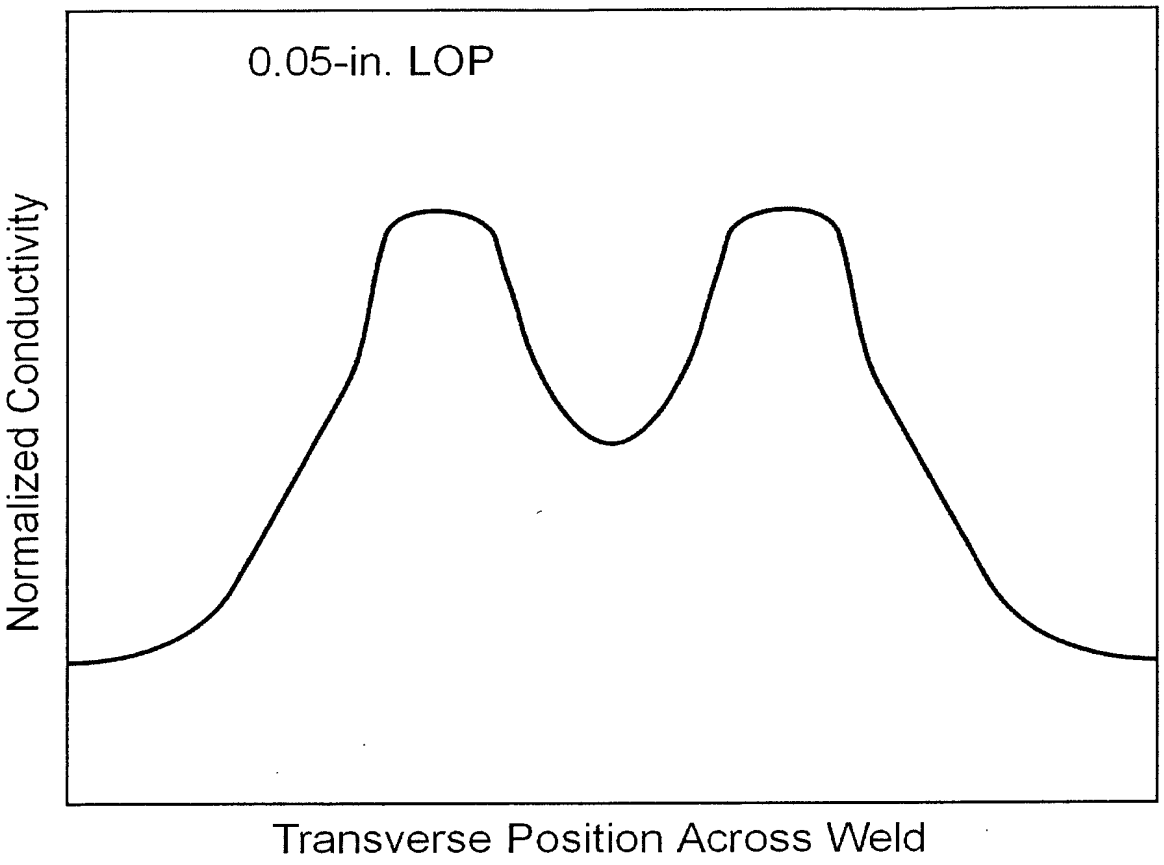
0.05-in. LOP
Normalized Conductivity
Transverse Position Across Weld

FIG 19

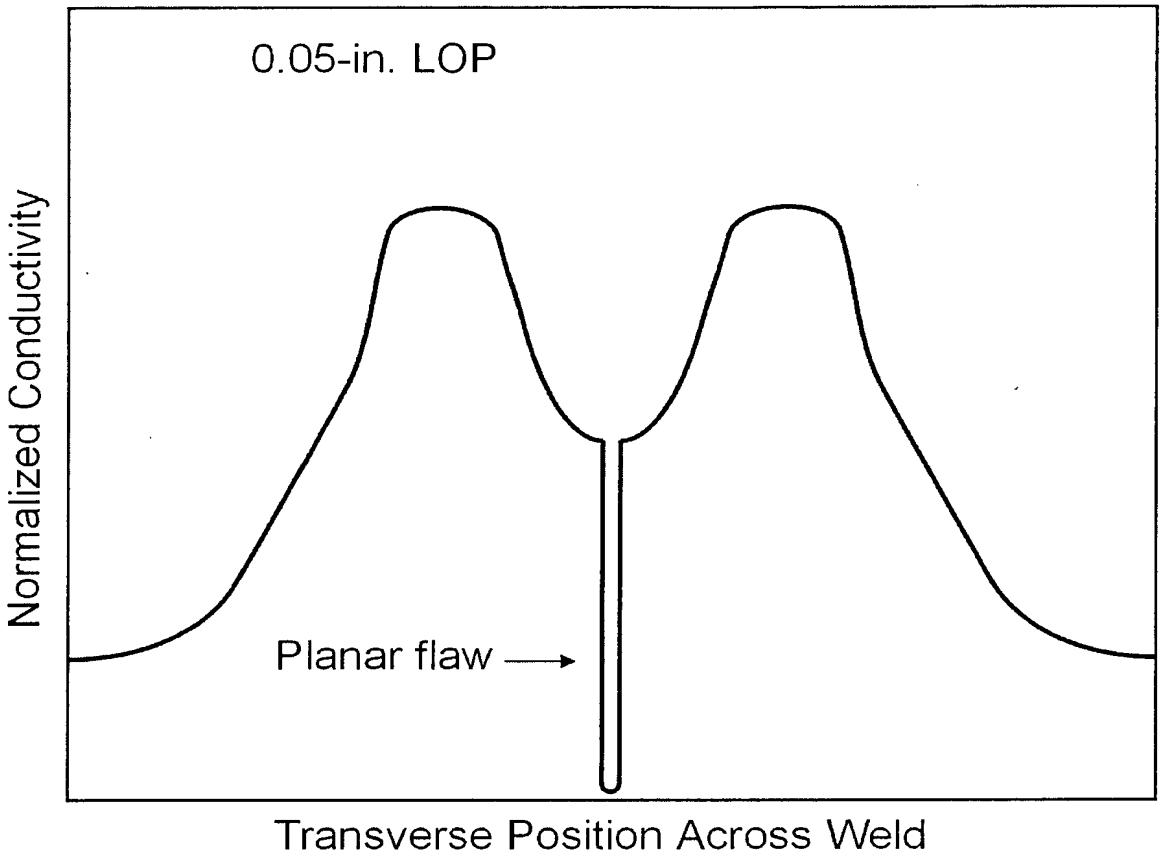
0.05-in. LOP
Normalized Conductivity
Planar flaw
Transverse Position Across Weld

FIG 20

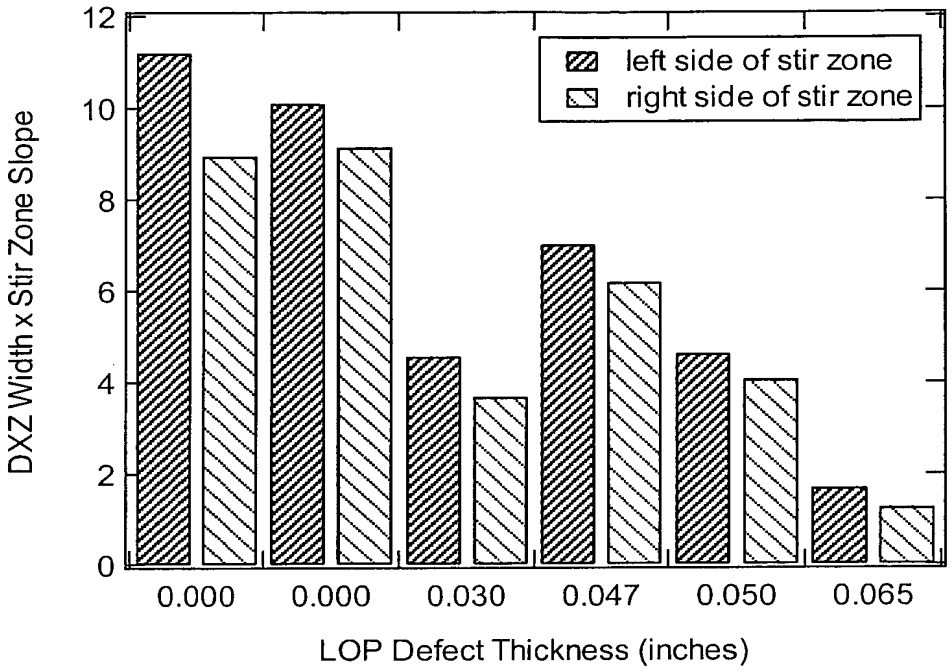
12
10
8
6
4
2
0
DXZ Width x Stir Zone Slope
left side of stir zone
right side of stir zone
0.000
0.000
0.030
0.047
0.050
0.065
LOP Defect Thickness (inches)

FIG 21

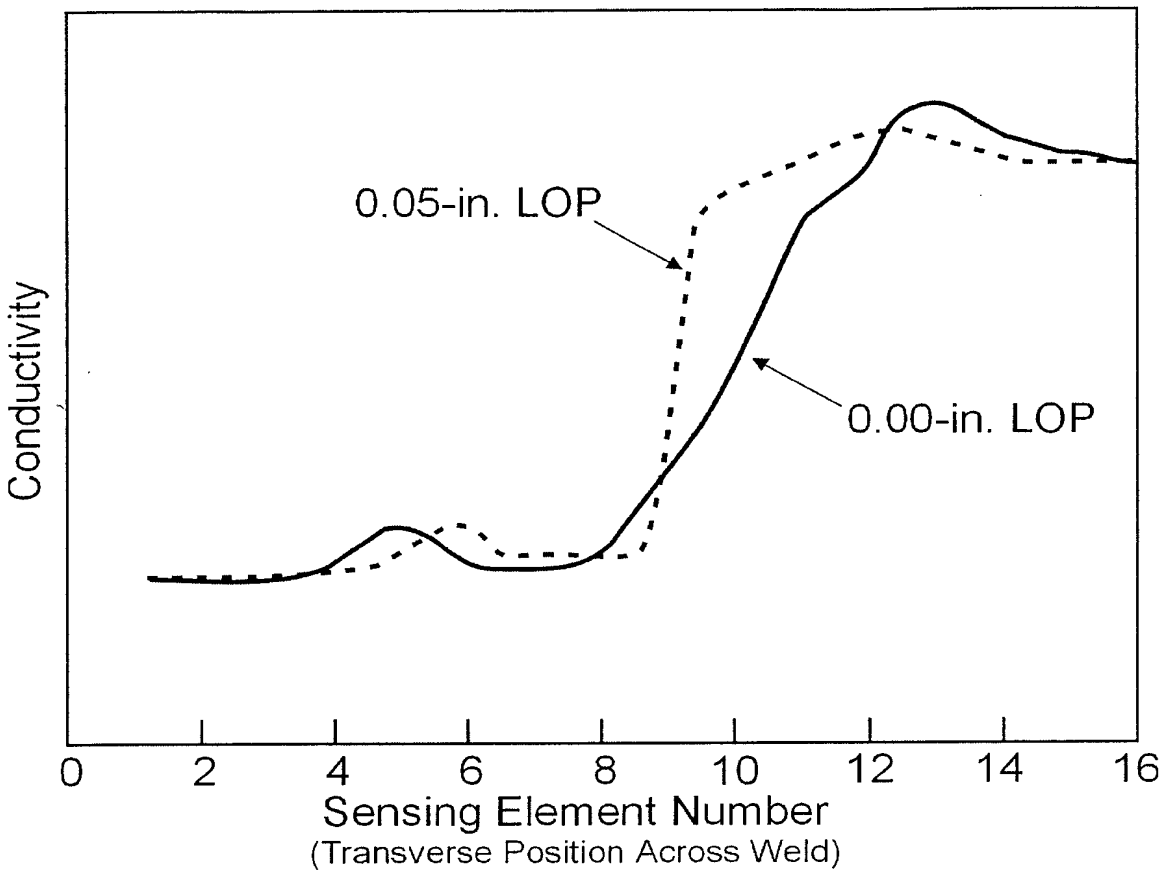
0.05-in. LOP
0.00-in. LOP
Conductivity
0
2
4
6
8
10
12
14
16
Sensing Element Number
(Transverse Position Across Weld)

FIG 22

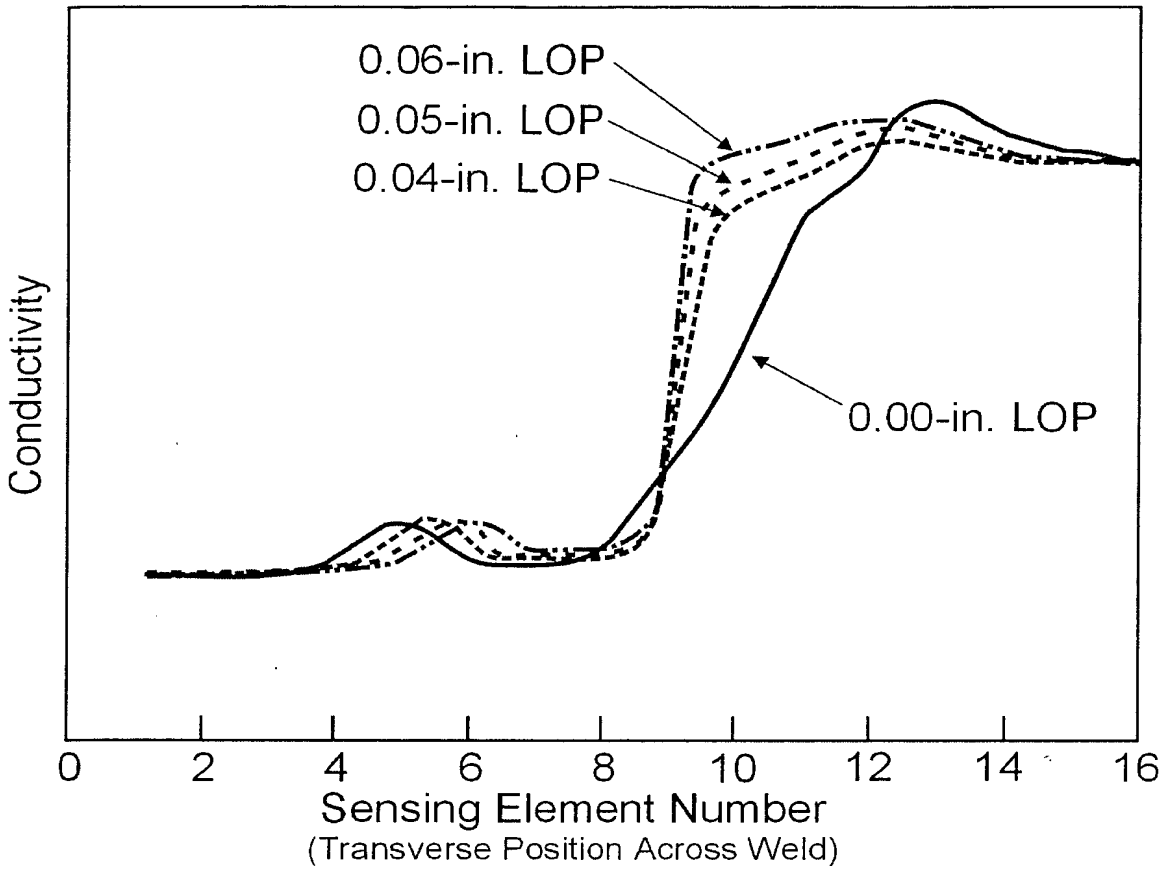
0.06-in. LOP
0.05-in. LOP
0.04-in. LOP
0.00-in. LOP
Conductivity
0
2
4
6
8
10
12
14
16
Sensing Element Number
(Transverse Position Across Weld)

FIG 23

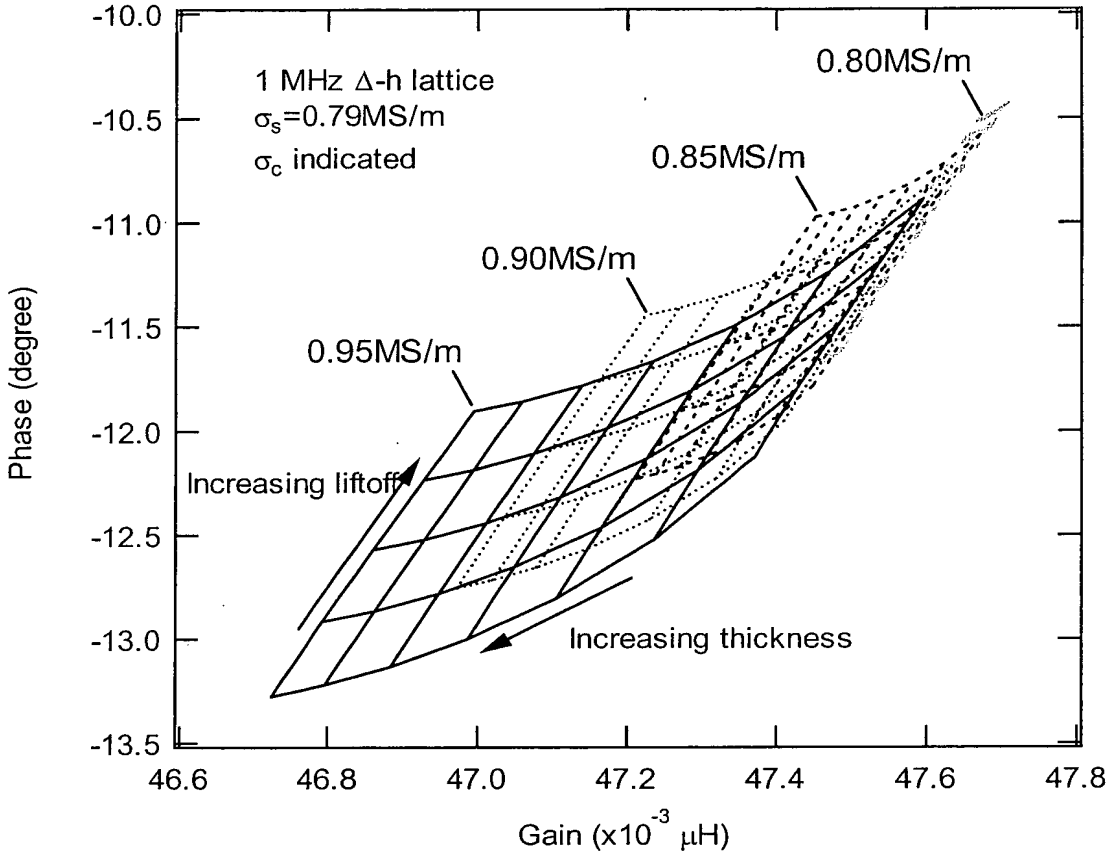
1 MHz Δ-h lattice
σ_s=0.79MS/m
σ_c indicated
0.80MS/m
0.85MS/m
0.90MS/m
0.95MS/m
Increasing liftoff
Increasing thickness
Phase (degree)
-10.0
-10.5
-11.0
-11.5
-12.0
-12.5
-13.0
-13.5
46.6
46.8
47.0
47.2
47.4
47.6
47.8
Gain (x10^{-3} μH)

FIG 24

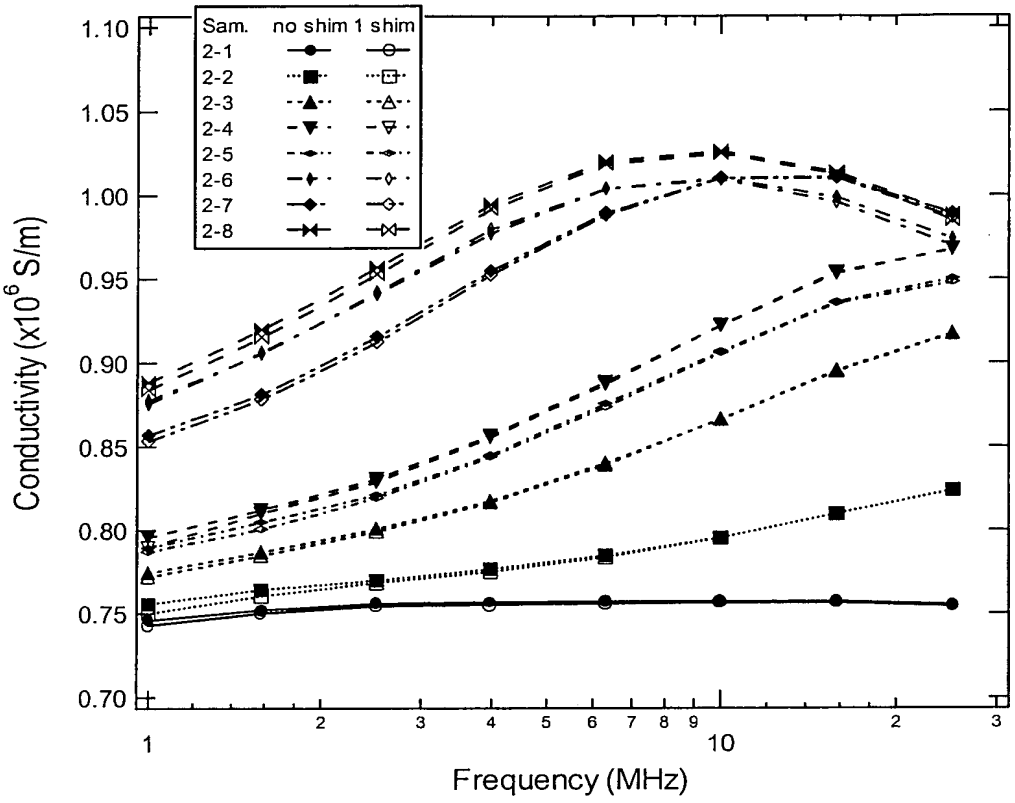
Sam. no shim 1 shim
2-1
2-2
2-3
2-4
2-5
2-6
2-7
2-8
1.10
1.05
1.00
0.95
0.90
0.85
0.80
0.75
0.70
Conductivity (x10^6 S/m)
1
2
3
4
5
6
7
8
9
10
2
3
Frequency (MHz)

FIG 25

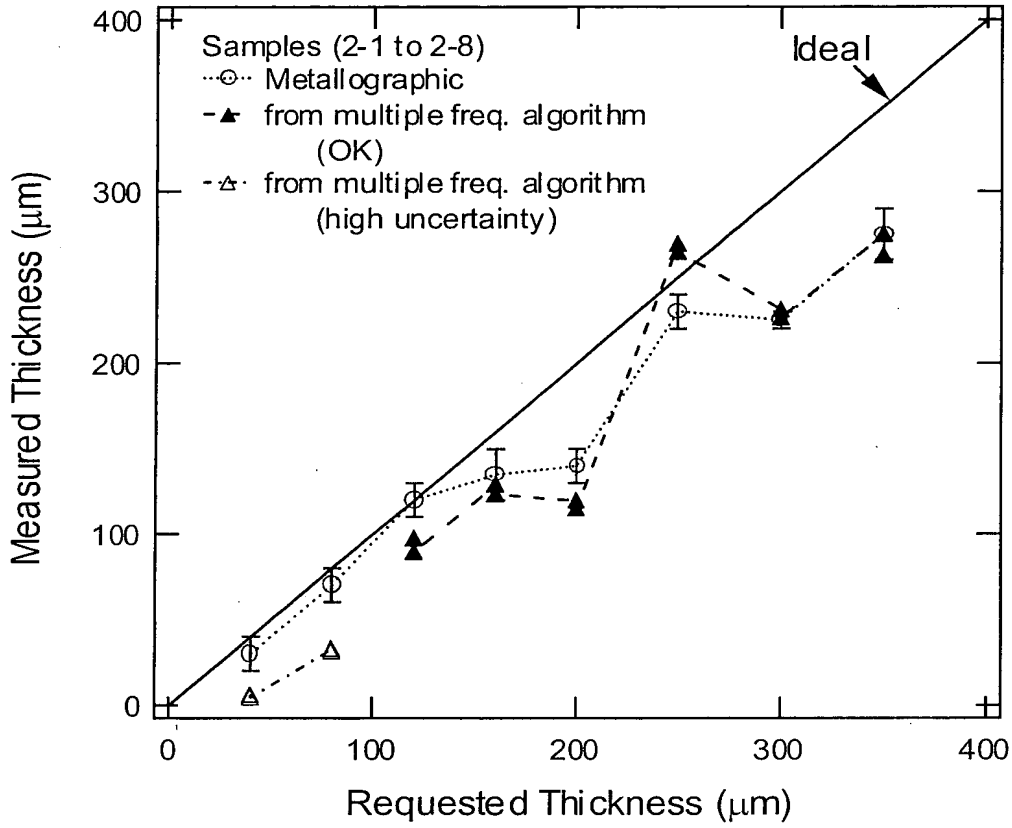
Samples (2-1 to 2-8)
Metallographic
from multiple freq. algorithm (OK)
from multiple freq. algorithm (high uncertainty)
Ideal
Measured Thickness (μm)
Requested Thickness (μm)
0
100
200
300
400

FIG 26

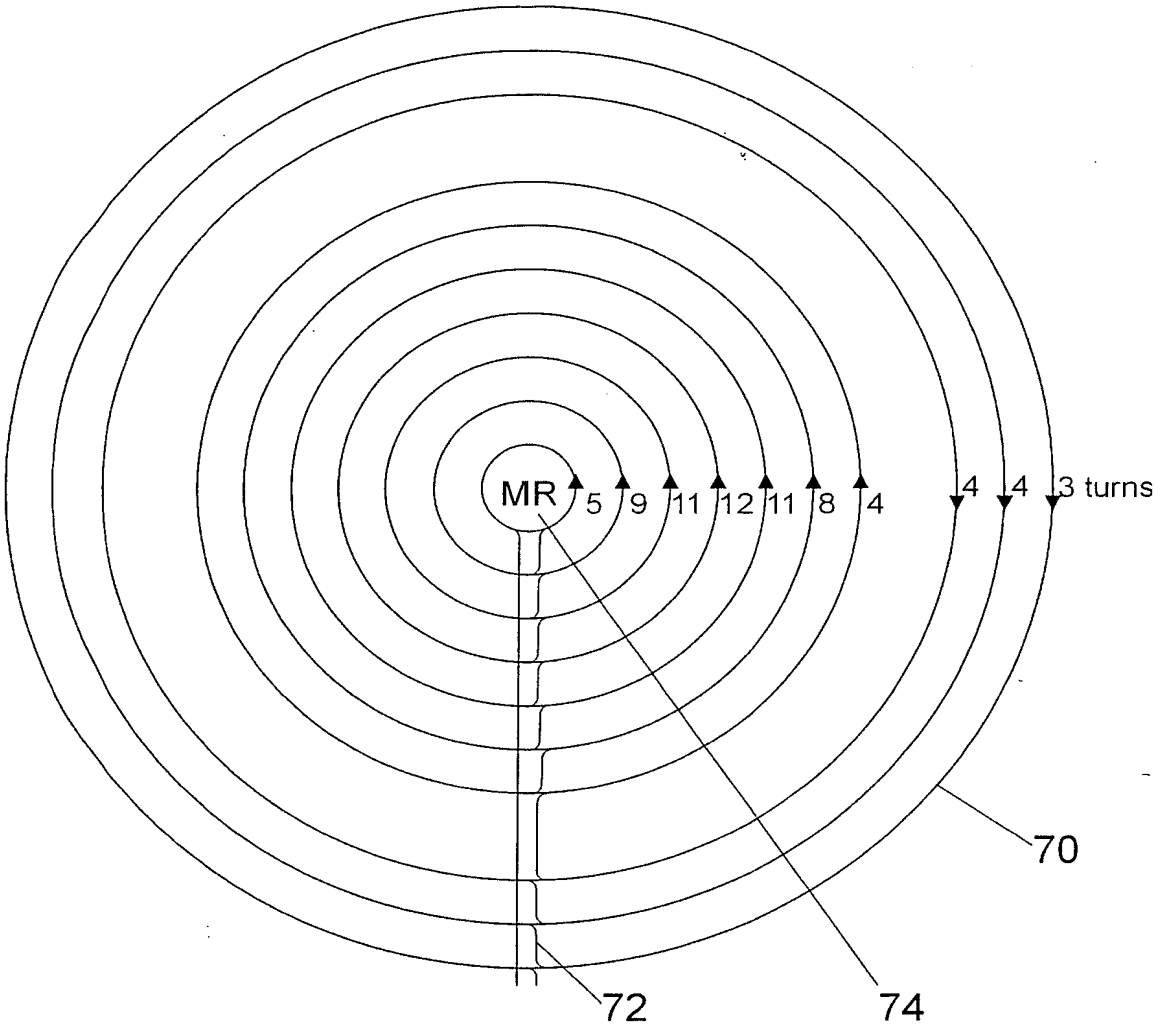

FIG 27

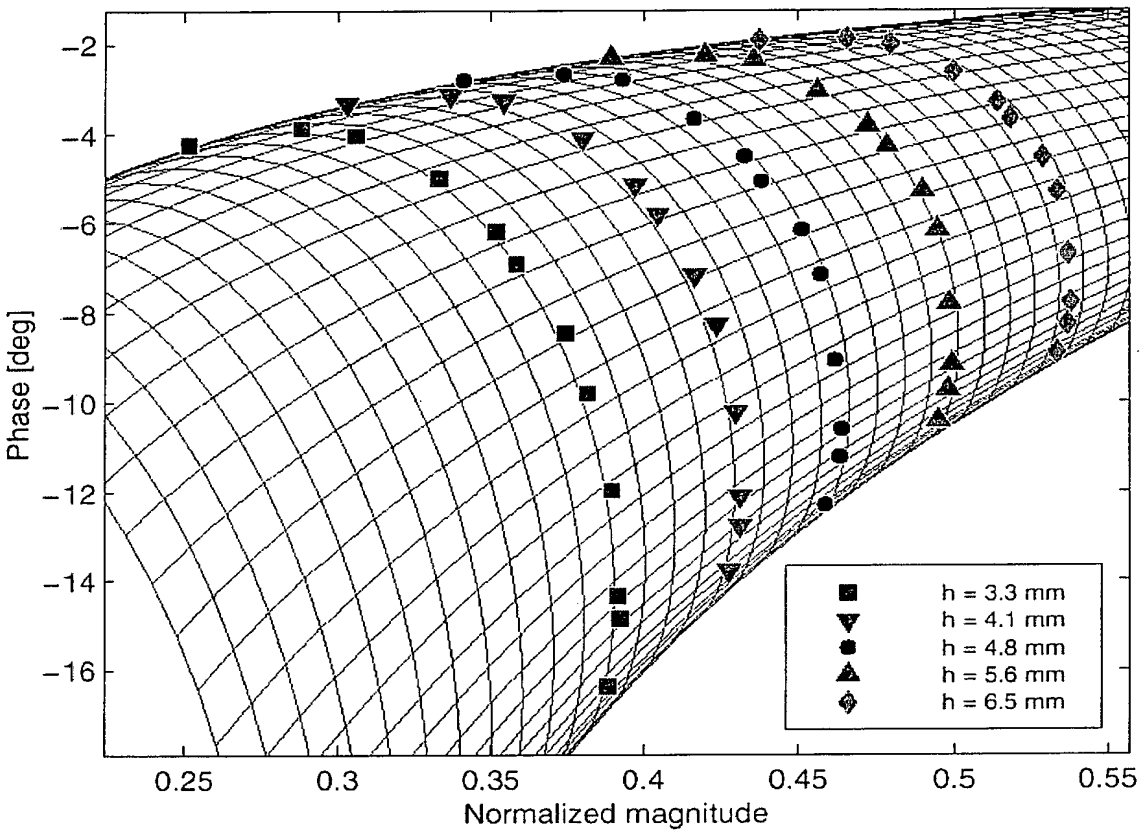
Phase [deg]
−2
−4
−6
−8
−10
−12
−14
−16
0.25
0.3
0.35
0.4
0.45
0.5
0.55
Normalized magnitude
h = 3.3 mm
h = 4.1 mm
h = 4.8 mm
h = 5.6 mm
h = 6.5 mm

FIG 28

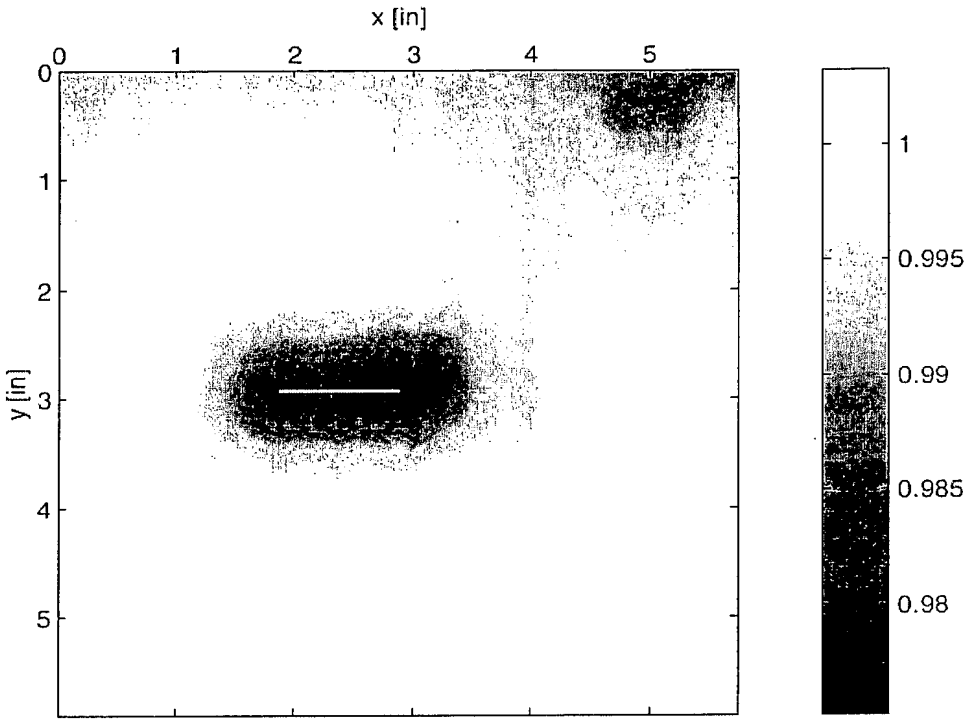

FIG 29

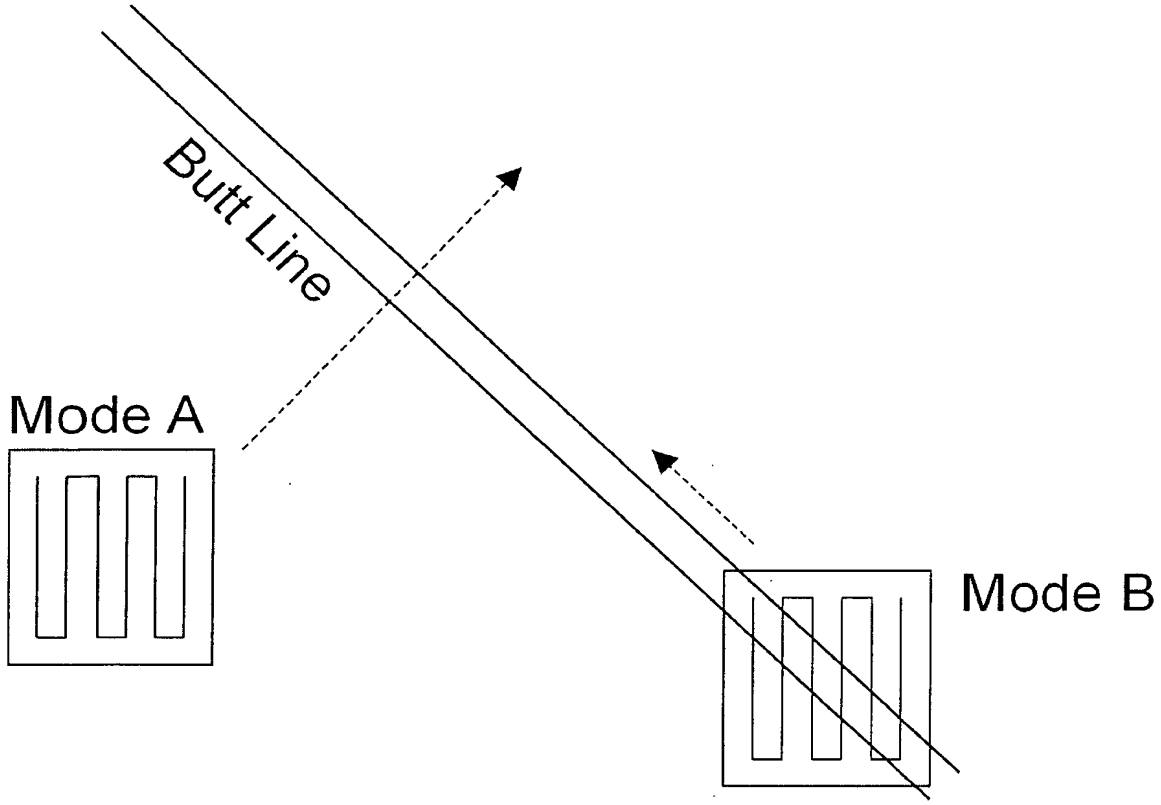

FIG 30

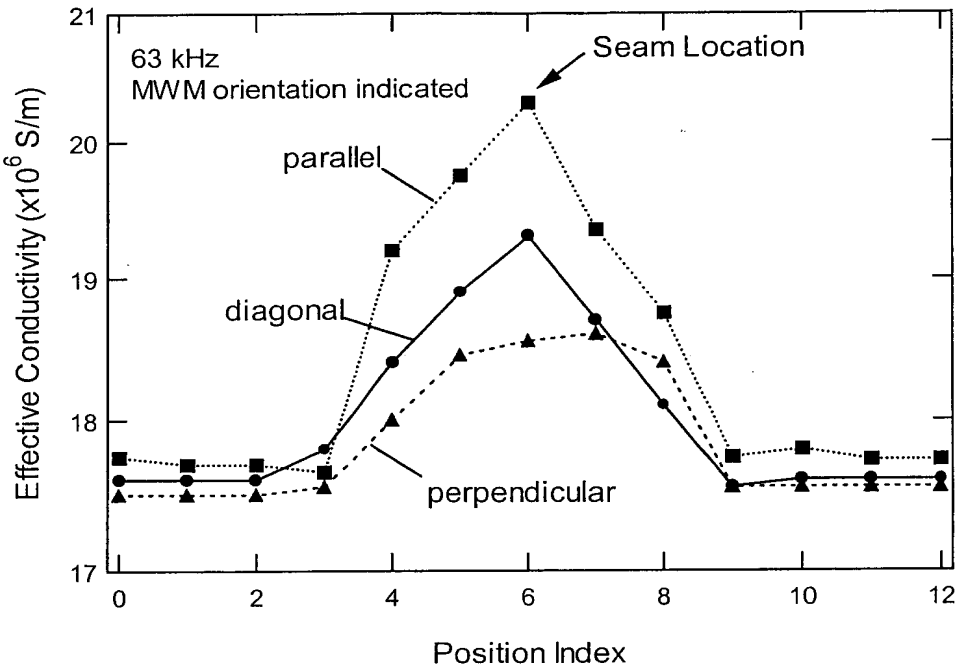
63 kHz
MWM orientation indicated
Seam Location
parallel
diagonal
perpendicular
Effective Conductivity (x10^6 S/m)
Position Index
21
20
19
18
17
0
2
4
6
8
10
12

FIG 31

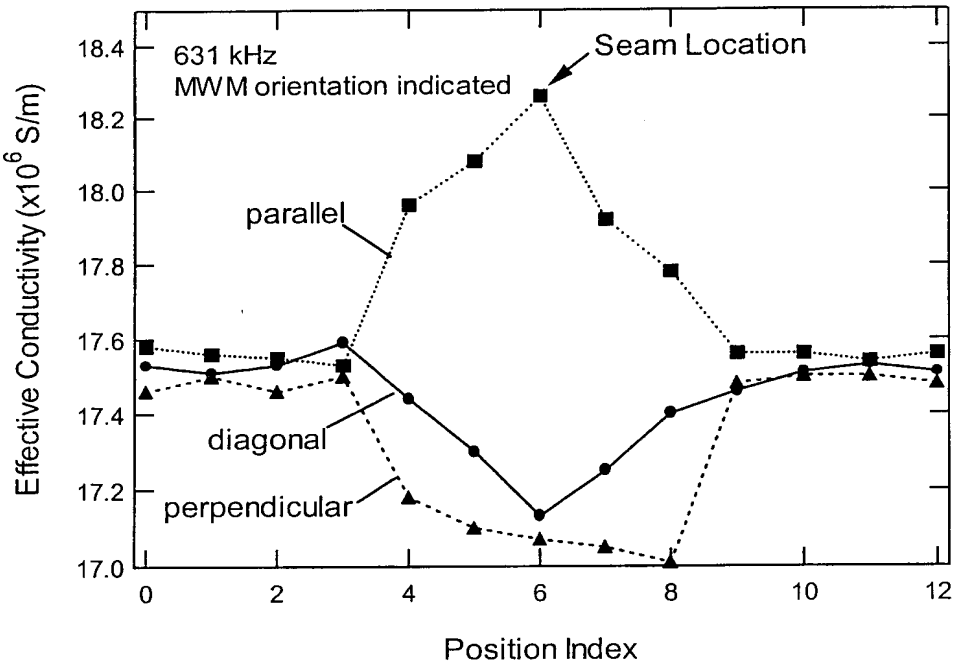
631 kHz
MWM orientation indicated
Seam Location
parallel
diagonal
perpendicular
Effective Conductivity (x10^6 S/m)
Position Index
18.4
18.2
18.0
17.8
17.6
17.4
17.2
17.0
0
2
4
6
8
10
12

FIG 32

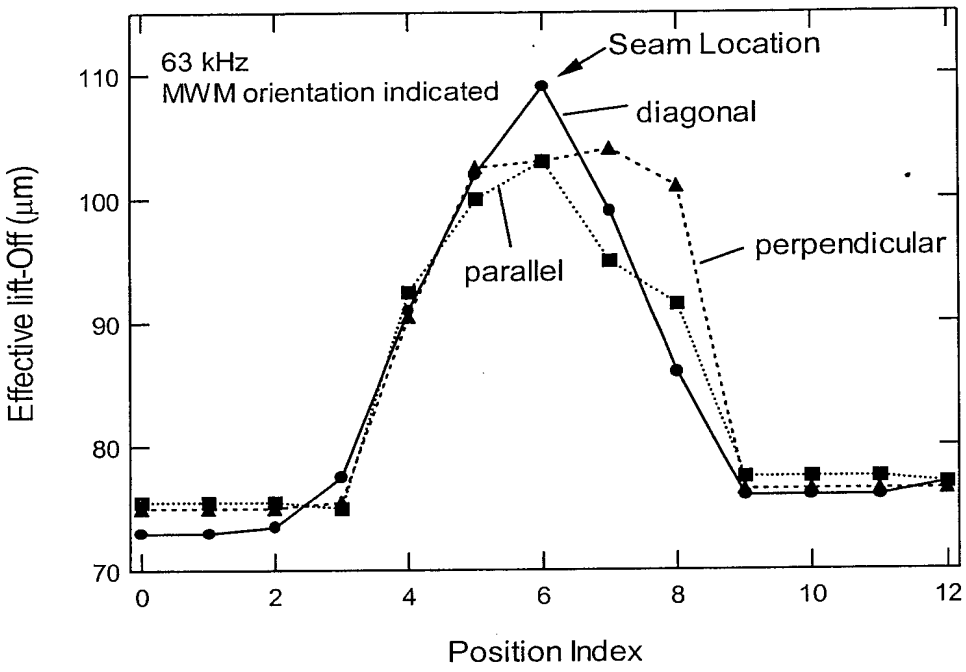
63 kHz
MWM orientation indicated
Seam Location
diagonal
perpendicular
parallel
Effective lift-Off (μm)
110
100
90
80
70
0
2
4
6
8
10
12
Position Index

FIG 33

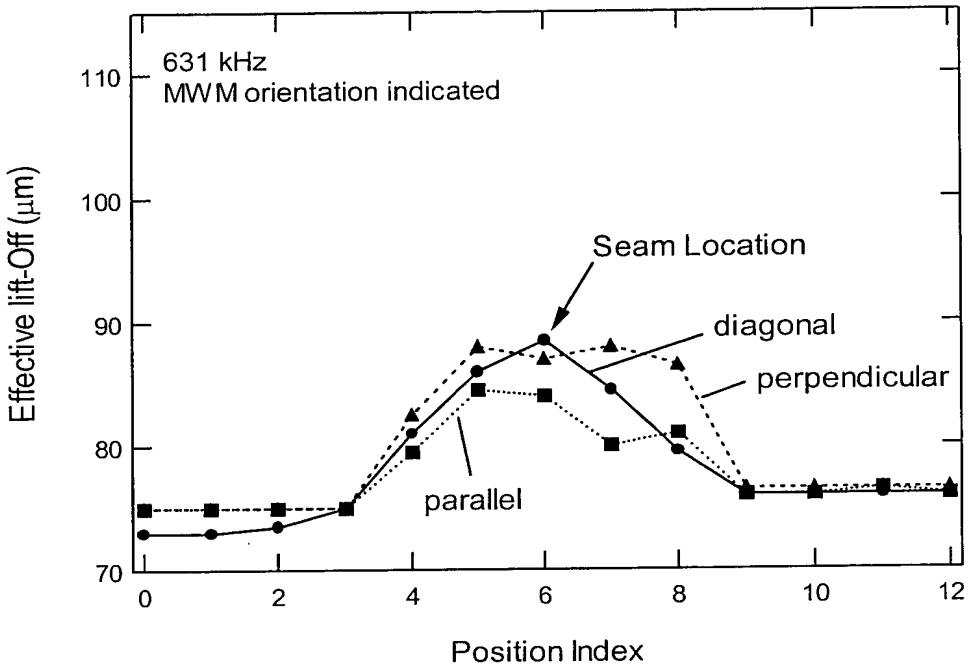
631 kHz
MWM orientation indicated
Effective lift-Off (μm)
110
100
90
80
70
0
2
4
6
8
10
12
Position Index
Seam Location
diagonal
perpendicular
parallel

FIG 34

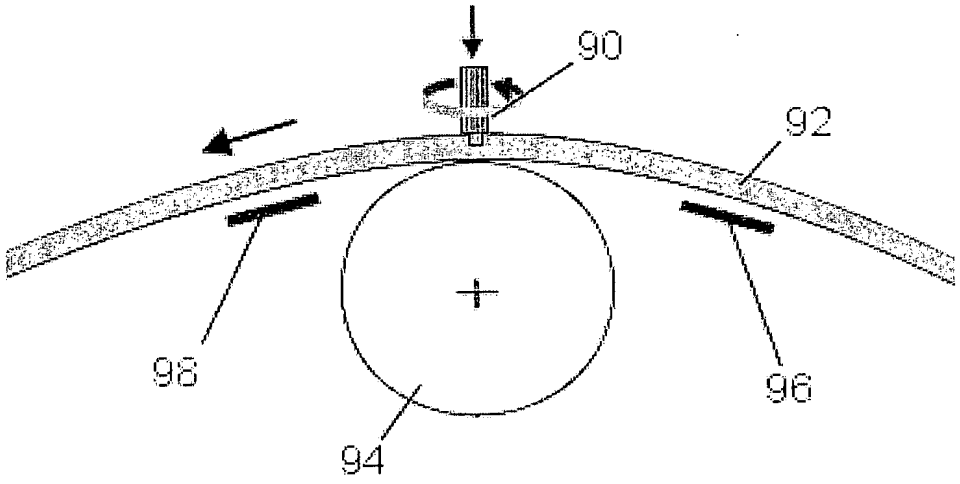
90
92
98
96
94

FIG 35